Discharge scheduling for voltage balancing in reconfigurable battery systems

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To manage thousands of battery cells effectively, a reconfigurable battery system has emerged where each battery cell is equipped with a set of switches for controlling connectivity (i.e. series, parallel, bypass or combinations thereof). While most studies have focused on maximising operation-time or life-time of a reconfigurable battery system, few studies have addressed how to quickly balance voltage of cells, which affects both efficiency and safety of a battery system. A new discharge scheduling policy for battery cell voltage balancing for a reconfigurable battery system is proposed. Based on the analysis why existing naive approaches are not effective for voltage balancing, a new approach consisting of three steps is designed: determination of a set of battery cells to be discharged, calculation of a target voltage, and distribution of the system load to each battery. The present simulation results show that the proposed approach outperforms three alternative ones up to 45.6% in terms of voltage balancing.

Introduction: Large-scale battery systems consisting of hundreds/thousands of battery cells have become popular for many electric systems such as energy storage systems and electric vehicles, and reconfigurable architecture has been studied in order to exploit the ability to control connectivity (i.e. series, parallel, bypass or combinations thereof) [1–4]. While most studies for reconfigurable battery systems have dealt with operation-time or life-time issues [1, 2], few studies have addressed how to quickly balance voltage of cells, which affects both efficiency and safety of battery systems [5].

In this Letter, we propose a new discharge scheduling policy for battery cell voltage balancing for a reconfigurable battery system. We first investigate why existing naive approaches (that directly balance voltage or state of charge of each battery cell) are not effective for voltage balancing. Based on the investigation, we then design the proposed approach with three steps: determination of a set of battery cells to be discharged, calculation of a target voltage, and distribution of the system load to each battery. Using a popular battery simulator Dualfoil [6], we demonstrate that the proposed approach outperforms three alternative ones up to 45.6% in terms of voltage balancing, which is the main contribution of the Letter.

Target system: A reconfigurable battery system was designed to control the connectivity of batteries in an arbitrary manner, and has been widely studied due to its potential in improving battery efficiency [1, 2]. A battery cell in a reconfigurable battery system has multiple switches, which not only determine whether the battery is connected or bypassed, but also control the type of connection (i.e. parallel or serial) as shown in Fig. 1 of [2]. In this Letter, we target a reconfigurable battery system equipped with sensors which measure various battery parameters such as voltage, current and internal resistance [7].

Problem statement: The goal of this Letter is to balance battery cell's voltage in a reconfigurable battery system. To this end, we determine $L_i(t)$, load assigned to a battery cell i (denoted by B_i) at t, so as to achieve the following objective function:

$$\text{Maximise } t^{\text{total}} \overset{\text{def.}}{=} \int_{t^{\text{start}}}^{t^{\text{end}}} \delta(t)\,\mathrm{d}t \tag{1}$$

$$\text{subject to } L^{\text{sys}}(t) = \sum_{\forall B_i \in \mathcal{B}} L_i(t) \tag{2}$$

where t^{start} and t^{end} denote the time instants when the system starts and ends, respectively; $\mathcal{B}$ denotes a set of all battery cells. $\delta(t)$ is 1 (likewise 0) if the difference between the highest and lowest voltage among cells in the reconfigurable battery system at t is no larger (likewise larger) than the threshold ϵ. Let $L^{\text{sys}}(t)$ denote the given system load at t.

Naive approaches: In this section, we introduce two naive approaches for achieving the goal. In addition, we show the ineffectiveness of the two approaches in balancing voltage, which will be used for developing the proposed approach in the next section.

The first naive approach is to balance each cell's terminal voltage. For example, suppose that the system load is constantly 4C and there are two battery cells: B_1 with 3.97 V and B_2 with 3.77 V, which we simulate using Dualfoil [6]. To make those voltage same, B_1 is solely discharged with 4C rate in [0, 2), and reach 3.77 V at $t = 2$, as shown in Fig. 1*a*. On the other hand, B_2 takes rest in [0, 2), keeping its voltage of 3.77 V. If we distribute load equally with 2C rate after $t = 2$, B_2's voltage decreases while B_1's voltage increases, which is counter-intuitive. This happens due to recovery effect, which indicates that if a cell takes some rest after discharge, the cell recovers a portion of voltage due to the diffusion of charged ions inside of a battery cell [8].

The second naive approach is to balance each cell's SoC, which is known to exhibit better performance than the first naive approach [5]. For example, suppose that there are two battery cells: B_3 with 75% SoC and B_4 with 50% SoC at $t = 0$. As shown in Fig. 1*b*, B_3 is solely discharged until it has 50% SoC, which is $t = 3.75$, and thereafter, B_3 and B_4 are discharged with same load. If we focus on the interval [0, 3.75), the difference between the two cells' voltage becomes larger; moreover, for the interval after $t = 3.75$, it takes more than 5 min to exhibit sufficiently small voltage difference between B_3 and B_4. Therefore, the second naive approach not only takes long time for voltage balancing, but also yields incorrect results (i.e. voltage difference becomes larger until $t = 3.75$). This is also due to recovery effect, and therefore, we need to take the effect into account for developing the new approach.

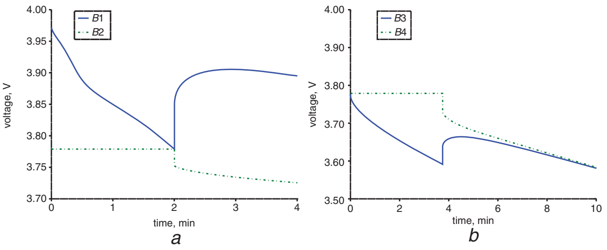

Fig. 1 *Two naive approaches for voltage balancing*

a Load distribution according to current voltage
b Load distribution according to current SoC

Proposed approach: Our approach works for each time interval and consists of three steps: (i) determination of a set of battery cells to be discharged, (ii) calculation of a target voltage which the set of battery cells reaches after discharge, and (iii) distribution of the system load to each battery, which correspond Lines 1 and 2, 3, and 4 and 5 of Algorithm 1, respectively. From now on, we will omit '(t)' in notations used in the algorithm and its explanation, for simplicity of presentation. Now, we present details of the three steps.

The first step is to decide a set of battery cells to be discharged. This step is important because the set size explores tradeoff between the rate and stability of voltage balancing (i.e. the less battery cells to be discharged, the faster converge to the target voltage; on the other hand, the more battery cells to be discharged, the more battery cells reach the same (target) voltage, which yields better stability). To reduce the difference between the highest and lowest voltage among cells in $\mathcal{B}$ (called the maximum voltage difference between battery cells in $\mathcal{B}$), we choose several battery cells with the highest voltage; meanwhile, we should make the system load equal to the sum of the amount of discharge from a group of battery cells to be discharged. Therefore, we find n^{d}, the largest n^* such that the system load is larger than the sum of current discharged to achieve the voltage of the battery cell with the n^*th largest voltage, which is recorded in the following equation:

$$n^{\text{d}} \overset{\text{def.}}{=} \max n^* \text{such that } L^{\text{sys}} > \sum_{i=1}^{n^*} f^I(B_i, V_{n^*}) \tag{3}$$

where $f^I(B_i, V)$ denotes the required load for the ith battery cell to achieve the voltage V, to be detailed later. Once we have n^{d} in line 1 of Algorithm 1, the set of battery cells to be discharged is determined by $\mathcal{B}^{\text{d}}$ in line 2 of Algorithm 1. By the definition of n^{d}, the target voltage to be determined by the second step is between the voltage of the battery cells with the n^{d}th and $(n^{\text{d}} + 1)$th largest voltage.

Here, we explain how to calculate $f^I(B_i, V)$ in (3). From [9], the terminal voltage of a battery cell (V^{out}) can be modelled as follows:

$$V^{\text{out}} = V^{\text{oc}}(\text{DoD}) - I \cdot R^{\text{int}} - U \tag{4}$$

where $V^{\text{oc}}(\text{DoD})$, I, R^{int} and U denote open-circuit voltage for given depth of discharge of (DoD), the flowing current, constant interval resistance, and voltage drop not covered from recovery effect, respectively. From existing studies (e.g. [9]), we assume that the function $V^{\text{oc}}(\text{DoD})$ is known, and therefore calculate U in (4) using actual values of V^{out}, DoD, I and R^{int} measured at every interval. Finally, we can approximate $f^I(B_i, V)$ by the relationship between ΔI and ΔV^{out} assuming negligible change of R^{int} and U for a short interval Δt.

The second step is to calculate V^{target}, the target voltage for battery cells in $\mathcal{B}^{\text{d}}$. For a short interval Δt, R^{int} and U are regarded as constants in (4). Then, after drawing current $f^I(B_i, V^{\text{target}})$ from the ith battery cell for a short interval, its output voltage would be V^{target} as follows:

$$V^{\text{target}} = V^{\text{oc}}\left(\text{DoD} + \frac{f^I(B_i, V^{\text{target}}) \cdot \Delta t}{\text{Capacity}}\right) - f^I(B_i, V^{\text{target}}) \cdot R^{\text{int}} - U \tag{5}$$

For every battery $B_i \in \mathcal{B}^{\text{d}}$, we have (5). In addition, V^{target} satisfies the following constraint from (2), since battery cells in $\mathcal{B}^{\text{d}}$ should support the system load L^{sys}.

$$L^{\text{sys}} = \sum_{\forall B_i \in \mathcal{B}^{\text{d}}} f^I(B_i, V^{\text{target}}) \tag{6}$$

Then, using n^{d} equations for (5), and one constraint in (6), we can approximate V^{target}, which is recorded in line 3 of Algorithm 1.

The third step is to distribute the system load to every battery cell based on V^{target}. To compensate a difference between L^{sys} and the sum of all cells' load (which is calculated not exactly, but approximately), we distribute each cell's load in $\mathcal{B}^{\text{d}}$, with rate of the cell's load to the sum of all cells' load, which is recorded in line 4 of Algorithm 1. Also, battery cells not in $\mathcal{B}^{\text{d}}$ will rest, as shown in line 5 of Algorithm 1.

Algorithm 1: Discharge ($\mathcal{B}$, L_{sys})

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1: Calculate $n^{d}$ using (3).
2: Sort $\mathcal{B}$ in decreasing order of voltage, and
   $\mathcal{B}^{d} \leftarrow \{B_i | i = 1, 2, \ldots, n^{d}\}$.
3: Calculate $V^{target}$ satisfying (5) and (6).
4: For every battery $B_k \in \mathcal{B}^{d}$,
   $L_k \leftarrow L^{sys} \times \left( \left( f^I(B_k, V^{target}) \right) / \left( \sum_{i=1}^{n^d} f^I(B_i, V^{target}) \right) \right)$.
5: For every battery $B_k \notin \mathcal{B}^{d}$, $L_k \leftarrow 0$.
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Evaluation: To evaluate the performance of the proposed approach, we use Dualfoil [6], one of the most popular battery simulators. We also choose 42 load samples from real load data in [10], which is obtained by electric vehicles driving cities in US. For simulation, we scale down each load sample such that the maximum load becomes 10C. Our simulation uses four Li-ion battery cells whose cut-off voltage is 2.0 V, and we set the interval length to 3 s.

We target a reconfigurable battery system consisting of four batteries whose SoC are set to 100, 95, 90 and 85%, respectively, and compare the following approaches.

- Ours: the proposed approach,
- kRR: kRR scheduling [2], which distributes load proportionally to each SoC for k cells with the highest SoC, where k is determined by recovery efficiency,
- RCS: redundant cell scheduling [11], which evenly distributes load to all battery cells except the cell with the lowest SoC, and
- SoC: SoC scheduling, which distributes load proportionally to each SoC for all cells.

We measure the maximum voltage difference (i.e. the difference between the highest and lowest voltage among cells in $\mathcal{B}$). Then, we can directly calculate t^{total} for given threshold $\epsilon = 0.05$ V. Fig. 2*a* presents the ratio of t^{total} of each scheduling to that of kRR, which is average of 42 load samples. As shown in the figure, kRR outperforms RCS and SoC, but ours exhibits 13% better performance than kRR in terms of average t^{total}. Moreover, ours extends t^{total} 45.6% longer, compared to kRR for a particular load sample. To investigate how ours effectively balances voltage, we select a sample among the 42 samples and present the maximum voltage difference of the four approaches over time in Fig. 2*b*. As shown in the figure, ours can effectively reduce the maximum voltage difference, while others cannot.

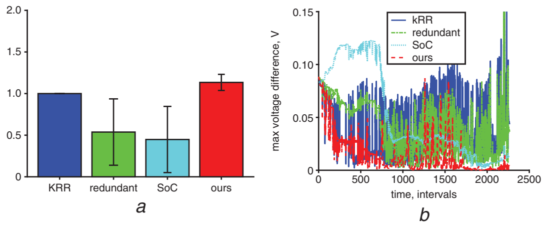

Fig. 2 *Simulation result*
a t^{total} (average)
b Maximum voltage difference

Conclusion: In this Letter, we addressed a voltage balancing problem in a reconfigurable battery system. The proposed discharge scheduling approach effectively reduces the voltage difference among battery cells – up to 45.6% improvement over existing approaches.

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One or more of the Figures in this Letter are available in colour online.

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